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Evaluation of methodologies for remunerating wind power's reliability in Colombia

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ABSTRACT

Colombia strives to have enough firm capacity available to meet unexpected power shortages and peak demand; this is clear from mechanisms currently in place that provide monetary incentives (in the order of nearly US$ 14/MW h) to power producers that can guarantee electricity provision during scarcity periods. Yet, wind power in Colombia is not able to currently guarantee firm power because an accepted methodology to calculate its potential firm capacity does not exist. In this paper we argue that developing such methodology would provide an incentive to potential investors to enter into this low carbon technology. This paper analyzes three methodologies currently used in energy markets around the world to calculate firm wind energy capacity: PJM, NYISO, and Spain. These methodologies are initially selected due to their ability to accommodate to the Colombian energy regulations. The objective of this work is to determine which of these methodologies makes most sense from an investor's perspective, to ultimately shed light into developing a methodology to be used in Colombia. To this end, the authors developed a methodology consisting on the elaboration of a wind model using the Monte-Carlo simulation, based on known wind behaviour statistics of a region with adequate wind potential in Colombia. The simulation gives back random generation data, representing the resource's inherent variability and simulating the historical data required to evaluate the mentioned methodologies, thus achieving the technology's theoretical generation data. The document concludes that the evaluated methodologies are easy to implement and that these do not require historical data (important for Colombia, where there is almost no historical wind power data). It is also found that the Spanish methodology provides a higher Capacity Value (and therefore a higher return to investors). The financial assessment results show that it is crucial that these types of incentives exist to make viable wind projects in Colombia at US$ 2000/installed kW. With the absence of these incentives the Project's NPV would be negative before and after-taxes. Additionally, it is demonstrated that wind power projects would only be viable in Colombia if the price of CERs is at least US$ 20/CO_2e ton. Furthermore, it is concluded that income tax exemptions are not enough to encourage wind power development in Colombia.

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Firm capacity is a concept widely utilized among power planners and regulators in Colombia, which is defined as the energy that generation companies can produce during scarcity periods.

Currently wind power contributes to 0.1% of the electricity needs of Colombia, with just one wind farm (Jepírachi Project[3]) of 19.5 MW installed, generating ~50 GW h annually. However, this capacity is minimal, compared to the resource potential in the country. The resource in the northern part of Colombia (La Guajira) has the potential to satisfy more than the country's energy demands[4] (the estimated capacity has been estimated to be around 21,000 MW [1]). In fact, the wind regime in Colombia is among the best in South America. Offshore regions of the northern part of Colombia have class 7 winds (over 10 m/s). The annual wind energy potential per square meter in some coastal regions is shown in Table 1.

1. Introduction: calculating wind power capacity in Colombia and around the world

Currently in Colombia there is a mechanism to remunerate the firm capacity of energy generators through the assignation of firm energy obligations. This mechanism, which until recently was termed Capacity Charge is now termed *cargo por confiabilidad* (Reliability Charge) (approved through resolution CREG 071 of 2006) [2].

Said resolution indicates the guidelines and the breadth for the calculation and remuneration of firm energy (ENFICC) based on the reliability that different energy generators contribute to the system. ENFICC is defined as the maximum electric power that is capable of delivering a power plant in extreme conditions of low volumes of water in reservoirs, in a continuous manner, during a year [3]. In this manner, each generating company that wishes to sell their firm energy participates in firm energy obligation (OEF) auctions.

However, this resolution CREG 071 of 2006 does not include in its proposed methodologies the calculation of firm energy for intermittent sources of energy, such as wind power and other alternative energy sources. Instead, it only considers conventional sources (e.g. hydro and thermal technologies), and treats plants not centrally dispatched in a general form regardless of the technology. As a consequence, because there are no approved methodologies for calculating their firm energy, any possible wind generator would not be able to participate in the firm energy auctions. In this way, alternative energy technologies are not being able to benefit from the important income that other conventional generators are able to receive and that could make an alternative energy project financially viable.

There are some obstacles to the implementation of alternative energies (such as wind) in Colombia [4]:

- High initial investment costs.
- Energy pricing does not include the additional benefits of alternate sources of energy, such as, market price stability, environmental protection and rural development among others.
- High production costs (above the price it costs to produce electricity over traditional sources of energy).
- Inability to control their production according to the dispatch of firm energy (due to variability/intermittence).
- Inability to maximize their production according to the maximum marginal price of the electricity market.

Due to the obstacles that renewable energies currently face and to the benefits that can be obtained from the low carbon generation from renewable energy sources such as wind power, there is a need to consider mechanisms that remunerate the possible reliable power that these sources can guarantee, thus resulting in income that will allow them to compete in the energy market. Due to the important financial incentive that firm energy remuneration represents, and to the fact that Colombia laws call for no discrimination in energy technologies, the authors find that it is crucial that a methodology be developed to calculate the firm energy of wind power.

Based on the above, methodologies for the calculation of the capacity of the wind power were identified globally, finding that many markets do recognize the generation capacity that wind power offers to the generation and distribution portfolio (even if the value that is recognized from wind power is lower that recognized and remunerated for other generation technologies).

In the analysis of the methodologies it was found that although in many markets the reliability of wind power is recognized, the methodologies to determine the firm energy of this generation source varies according to the generating companies or distribution utilities and to factors such as location, the development of the market and penetration percentage of the resource within the generation portfolio.

Table 1
Wind power potential in selected regions of the Atlantic Coast of Colombia, at 10 m height.

Location	Wind power in kilowatt hours per square meter per year (kWh/m^2/yr)
Cabo de la Vela	3043
San Andrés	2182
Providencia	1727
Rioacha	829
Soledad	633
Cartagena	587
Valledupar	502

Source: UPME, 2000.

[3] The pilot Jepírachi Carbon Offset Wind Power Plant project was developed by one of Colombia's largest utilities (EPM) in collaboration with the German Technical Cooperation Agency (GTZ) during the feasibility phase, and with the World Bank in its CDM aspects. The project began operation in April 2004. Jepírachi is the first energy project in Colombia to apply to the CDM. The project is expected to displace an estimated ~430,000 metric tons of CO_2 until 2019 (World Bank 2007). The total installed capacity is 19.5 MW, generated by 60-m-high 15 turbines (Nordex60) at 1300 kW each.

[4] Should there not be technical constraints to fully supply a system with wind power.

Of the methodologies analyzed, those that are more flexible in data requirements were chosen. This is important in the Colombian context where wind regime data is largely unavailable. In the following sections, the authors describe the methodologies selected to then evaluate these under a simulated wind regime characteristic of Colombia. The last sections then present a proposal for implementation, under the point of view of the investor.

2. PJM Interconnection

PJM Interconnection ISO/RTO is a regional transmission utility in the United States and is also the greatest competitive electricity market in the world. PJM delivers energy to the following US states: Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. Since 2003 PJM established rules and procedures for determining the generating capability of variable resources. These procedures allow for the full participation in the energy market of producers that generate from variable resources, and thus even compete with conventional power generators such as hydro or nuclear power plants[5] [5].

In this methodology, capacity credits are calculated based on the net Capacity Value of all the participant generators, and the individual Capacity Value is calculated based on the generator performance, be it or not, a generator that uses conventional or intermittent resources, such as wind.

PJM makes a difference between the wind power generators based on the years of operation data and experience using this resource. They are classified as "mature wind farms" if it has at least three years of operation; if not, they are classified as "immature wind farms".

The calculation of a Capacity Value assigned to a particular wind generator in a particular wind farm for a particular year n is performed by computing the mobile average of the unique single year capacity factors for each of the three last summer periods. Those single year capacity factors are based upon operating data for each year. When the current capacity factor is multiplied with the current Net Maximum Capacity the result is the current year's capacity factor for that particular generator or wind farm.

However, if the power generator is classified as "immature", the single year capacity factor is assigned the value of the "*Wind Class Average Capacity Factor*" for each summer period where there is no operation or incomplete operation data. This "Wind Class Average Capacity Factor" is initially set as 20%, but it is subject to change if new operating data are available from nearby wind farms upon which to base the analysis of this factor.

The methodology for calculating the generating capacity of variable resources, especially wind farms, according to PJM is as follows:

1. Sum of all the hourly outputs for each of the summer peak hours in the year for three years prior to the current year:

$$\sum_{i}^{n} P_{si} \ \text{[MW]} \tag{1}$$

where P_{si} is the hourly output for each of the summer peak hours.

The summer period in the USA is defined as the period from June 1 through August 31 and "Peak Hours" are those between 3:00 and 6:00 pm [5].

2. Sum all of the Net Maximum Capacity Installed Values and their respective hourly outputs for each of the summer peak hours in the year for three years prior to the current year.

$$\sum_{i=1}^{n} (P_{si} + CN_i) \ \text{[MW]} \tag{2}$$

where CN_i are the Net Maximum Capacity Values. If the Net Maximum Capacity is nearly constant for the years of analysis, for calculations purposes, the average value of the respective years can be used. PJM defines the Net Maximum Capacity as: CN_i: Nominal Power – Auxilary Services power [MW]

3. The capacity factor for each of the prior years is calculated as follows:

$$\frac{CF_n = \sum_{i=1}^{n} P_{si}}{\sum_{i=1}^{n} (P_{si} + CN_i)} \ \text{[MW]} \tag{3}$$

If there is no operating data for immature wind farms, then the capacity factor that is assigned for the single year is the previously mentioned 20% Wind Class Capacity Factor [5].

4. The capacity factor to be used in the current year is the mean (arithmetic average) of the three single year capacity factors calculated in the steps above.

$$CF_n = \frac{CF_{n-1} + CF_{n-2} + CF_{n-3}}{3} \tag{4}$$

5. The current Capacity Value is then calculated by multiplying the capacity factor, CF_n, by the current Net Maximum Capacity Factor.

$$\text{Capacity Value}_n = CN_i * CF_n \ \text{[MW]} \tag{5}$$

In all cases, Capacity Values calculated for Wind Farms are applicable for the entire calendar year, from January 1 through December 31.

This process accommodates any changes in the Net Maximum Capacity Value for the wind farm for which the calculation is being computed.

The Capacity Value represents the amount of generating capacity, expressed in MW, that the plant can reliably contribute during summer peak hours and which can be traded as Unforced Capacity credits in the PJM capacity market [5].

3. Spanish electric market methodology

The Spanish electric market considers alternative energy sources, such as photovoltaic or wind farms, under a special power production operating regime with special rules and procedures. The reasoning behind this is that these energy sources are believed to increase the overall net efficiency. In addition, it is acknowledged that the use of renewable energy resources produces lower environmental impact than other energy sources.

For wind power generation, the firm capacity calculation in the Spanish electric market is based on procedures (3.7 and 14.5) for variable resources, charges, and payment obligations to then establish the methodology to calculate the firm capacity guarantees [6]. This methodology is described below:

3.1. Minimum monthly operation hours

Only those generation units with at least 50 proved operation hours at full generation rate can participate in the power guaranty payback.

The total operation hours $NHOR(a-1, up)$ of the generation unit up in the year $a-1$ (that is, the year prior to the one under the current analysis) are calculated by summing the total energy delivered in MW h and dividing this by the total nominal power

[5] The rules and procedures can be found in PJM's manual 21 of 2005.

MW, as follows:

$$NHOR(a-1, up) = \sum_{m}\sum_{d}\sum_{h}\frac{\max(0, MED(up, h, d, m))}{PNI(d, m)} \quad (6)$$

where $MED(up, h, d, m)$ is the amount of energy produced during the month (hours h, of the day d, of the month m), for the year $a-1$. If this data is unknown, the actual amount of power generated (MW h) of the generation unit up, in the h period, $MED(up, h, d, m)$ will be zero. $MED(up, h, d, m)$ is the nominal power capacity of the production unit up of the day d in the year $a-1$. $PNI(d, m)$ is the total nominal power in day d, of month m.

3.2. Firm power guarantee payback calculation

The firm power formula that is used for the power guarantee assignation ($PGP(up, m)$) of the generation unit up in the month m, is as follows:

$$PGP(up, m) = CMES(up, m) * CDIS(up, m) * PEQ(up, m) \quad (7)$$

where $CMES(up, m)$ is the ratio between the sum of all the monthly hours in which the generation unit has the right to receive a firm power payback guarantee and the number of $NH(m)$ hours of the corresponding month, e.g. 720 $CDIS(up, m)$ is the availability coefficient and is equal to 1 for generation units that do not depend on thermal processes, such as wind power. $PEQ(up, m)$ is the nominal power of the unit up in the month m (its formula is described below).

For generation units that use renewable resources and have more than one production unit, the $CMES(up, m)$ will be the weighted average of all the units with their respective real operation hours in the corresponding month, the calculation procedure is as follows:

$$CMES(up, m) = \frac{\sum_{d}\sum_{up} NH(d) * PEQ(up, d)}{NH(m) * \sum_{d}\sum_{up} PEQ(up, d)} \quad (8)$$

$PEQ(up, m)$ is the nominal power of the unit up in the month m, and is calculated as:

$$PEQ(up, m) = \frac{(PNIMM(up, m) + PMLDMP(up, m))}{2} \quad (9)$$

where $PNIMM(up, m)$ is the net monthly average nameplate power, and is calculated as:

$$PNIMM(up, m) = \frac{\sum_{d} PNI(up, d) * NH(d)}{\sum_{d} NH(d)} \quad (10)$$

$PNI(up, d)$ is the total nominal power of the generation unit up in the day d and $NH(d)$ is the number of hours of operation during day d. If the generation unit uses renewable resources, such as wind, $PNIMM$ will be the sum of the respective monthly nameplate power of all the generator devices that conforms the generation unit up.

On the other hand, the average power limited by the availability of resources, such as water for hydropower generation units or wind for wind farms, $PMLDMP(up, m)$ is calculated as:

$$PMLDMP(c, m) = \frac{1}{5}\sum_{a=1}^{5}\frac{PRDB(c, m, a)}{NH(m, a)} \quad (11)$$

where $PRDB(c, m, a)$ is the total production in the month m, of the year a, during the last 5 years of operation; which is valid for each power plant c that conforms the generation unit up and $NH(m, a)$ is the total production hours in the month m of the year a. If there is not enough generation data from one of the years of analysis, or if the generation unit has less than 5 years of operation, the $PMLDMP(up, m)$ will be calculated as the average power of the available operation years for the month m multiplied by 0.25.

3.3. Charges and payment obligations for firm power guarantees

These are the payments that every single generator has the right to receive. The payment is proportional to the firm power guarantee assigned and is calculated as follows:

$$DCGP(up, m) = RTGP(m) * \frac{PGP(up, m)}{\sum_{up} PGP(up, m)} \quad (12)$$

where $RTGP(m)$ is the payment for every single MW of power assigned as power guarantee for the month m to the generation unit up.

4. New York Independent System Operator – NYISO

The New York Independent System Operator (NYISO) manages New York's electricity transmission grid and oversees wholesale electricity markets [7]. The NYISO's Installed Capacity Market (ICAP) is based upon the Unforced Capacity that each Installed Capacity Supplier is qualified to supply. The capacity is calculated for each supplier by forecasting the contribution to its transmission district peak load, plus an additional amount to cover the Installed Reserve Margin. The capacity that each supplier can reliably supply to the system is determined by the "Unforced Capacity Methodology – UCAP".

The following are the requirements and a description of the NYISO Unforced Capacity Methodology:

4.1. Minimum Unforced Capacity requirements

Generators must follow certain procedures and provide information to the NYISO in order to qualify as Installed Capacity Suppliers. For variable resource generators, such as wind farms, it is mandatory to report the Maximum Net Capability (DMNC) which is the maximum net amount of power the generator may supply to the transmission.

In order to perform the DMNC testing, the Installed Capacity Suppliers may use historical generation data for the immediately preceding period, which cannot be older than 12 months.[6] For intermittent resources generators, such as wind power, the DMNC test is the sum of the nominal power of each of the generation units located in the wind farm. The report must include current and historical production data, programmed production hours, location and name of the intermittent resource, in this particular case, wind.

Once the DMNC testing is done and reported, it is reviewed and adjusted as necessary in compliance with the Installed Capacity Market current rules. If the reported DMNC is accepted, the generator can participate in the auction capacity market based on the accepted DMNC report.

4.2. Calculation of Unforced Capacity for Wind Generators

A Wind Farm's Unforced Capacity (*WFUCAP*) means the amount of generating capacity, expressed in MW, that a wind farm can reasonably be expected to contribute during the summer or the winter peak hours.

According to the NYISO definitions, the "Summer Peak Hours" means the hours beginning 14, 15, 16 and 17 from June 1 through August 31, and "Winter Peak Hours" means the hours beginning

[6] Generally, the calculation of the Production Factor for a particular Wind Farm for a particular Capability Period is based on its operating data for the Prior Equivalent Capability Period.

16, 17, 18 and 19, from December 1 through the last day of the immediately succeeding February.

The calculation procedure is as follows:

The *WFUCAP* for a particular wind farm and a particular capability period is the nominal capacity multiplied by the Production Factor, considering between those periods, any change in the nominal capacity that may have been made to the wind farm in the previous period.

The amount of Unforced Capacity that resource g is qualified to provide in month m is calculated as follows:

$$UCAP_{gm}^{q} = Pr\,odF_{gm} * NC_{gm} \tag{13}$$

where $Prod_{gm}$ is the Production Factor used in the calculation of the amount of Unforced Capacity that supplier g is qualified to provide in month m and NC_{gm} is the nominal or nameplate capacity of resource g that is applicable when determining the amount of Unforced Capacity that resource g is qualified to provide in month m.

The Production Factor is calculated as follows:

$$Prod = \frac{\sum_{h \in CPPH_{gm}} E_{gh}}{\sum_{h \in CPPH_{gm}} NC_{gh}} \tag{14}$$

where $CPPH_{gm}$ is the set of all summer (winter) peak hours during the most recent summer (winter) capability period, during which resource g was available for commercial operation; E_{gh} is the amount of energy delivery to the transmission system by resource g during hour h; and NC_{gh} is the nameplate capacity of resource g that was applicable when determining the amount of Unforced Capacity that the same resource was qualified to provide during hour h.

In the case of new wind farms for which production data are available for less than 60 days, the Production Factor is calculated by assuming tabulated factors, in accordance with the NYISO procedures. The value of these factors depends upon the location within the NYISO territories in which the wind farm is located and the corresponding period (summer or winter, as applicable)[7] [8].

5. Wind model development with Monte-Carlo Simulation

The methodologies explained in the previous three sections were evaluated for a wind farm under Colombian special conditions and then simulated under Monte-Carlo analysis with Excel.

As it was noted in Section 1, one of the main difficulties in establishing the firm capacity of wind generators in Colombia is the lack of historical wind data[8] [9]. EPM, the only company with actual records of wind measurements and power generation is reluctant to share the data it has obtained during the few years that its pilot project has been in place. For this reason, a Monte-Carlo based simulation model had to be developed in order to represent the possible wind regime of the area selected.

The selected zone for the simulation was the area named "Alta Guajira", in the northernmost coast of Colombia. This region has the largest wind power potential in the country according to the Colombian Wind Atlas [10]. Specifically data from the "Puerto Bolívar" meteorological station was taken for the simulation.

A Weibull distribution was used to simulate wind velocity, since previous mathematical and statistical studies indicate that this model is one of the most appropriate to represent natural wind distribution [11]. The Weibull distribution is continuous and has the following probability density function:

$$f(V, \alpha, \beta) = \frac{\alpha}{\beta}\left(\frac{V}{\beta}\right)^{\alpha-1} e^{-(V/\beta)^{\alpha}} \tag{15}$$

The random variable is wind velocity V in (m/s). The function is valid for all $V \geq 0$, where $\alpha > 0$ is the shape factor and $\beta > 0$ is the scale factor. These two factors are related to the mean and standard deviation of the distribution through the following equations [11]:

$$\alpha = \left(\frac{\sigma}{\overline{V}}\right)^{-1086} y \cdot \beta = \frac{\overline{V}}{\Gamma(1 + 1/\alpha)} \tag{16}$$

where $\overline{V}$ is the distribution mean and σ the standard deviation, and Γ is the gamma function.

Since the wind data is referenced at a height above surface of 10 m, to be applicable to larger generators these must be calculated at wind generator height of 60 m. Thus, the following wind velocity profile formula [10] must be used:

$$V = V_{ref}\left(\frac{Ln(Z/Z_0)}{Ln(Z_{ref}/Z_0)}\right) \tag{17}$$

where V_{ref} is the known velocity at a reference height, Z_{ref}; Z is the height at which velocity V is expected to be calculated; and Z_0 is the equivalent length of roughness according to terrain features. According to the characteristics of terrain in Alta Guajira, an equivalent roughness of 0.03 m was selected[9] [12].

Wind velocity series are generated using the Monte-Carlo simulation and velocity values are adjusted to the Weibull probability distribution.

A random number is generated according to the uniform distribution (U) in the (0, 1) interval and then wind velocity is adjusted to a Weibull distribution with parameters α and β from the following relation [13]:

$$V = \beta(-Ln(U))^{1/\alpha} \tag{18}$$

where V is wind velocity generated from the distribution mean, standard deviation, and α and β parameters.

Each wind velocity value generated represents a random value of power generated. In this way 10,000 values of power and velocity are obtained.

The wind model developed only considers monthly seasonality, that is, month to month variation during a year, assuming that this behaviour will remain constant during the project's useful life. Under this assumption, inter-daily seasonality effects are not included, as well as possible effects that may affect the wind regimes during different years, such as "El Niño" phenomenon or other possible climate factors that may affect the wind behaviour in the selected region. In regard to this last point, it is assumed that there is no correlation between "El Niño" phenomenon (which translates into a period of critical hydrology in Colombia) and the wind regime.

Table 2 presents the α, β, wind mean velocity (m/s) and standard deviation (m/s) monthly values at 60 m height that were used for the simulation of wind velocity and power generated.

The hourly generated energy (kWh) is obtained from the power curve of the wind generator, according to generated wind velocity values. For this, the NORDEX N60/1300 generator was selected. Fig. 1 illustrates the power curve of this wind generator, as well as the regression equation obtained for this curve[10] [14]:

[7] These Production Factors range between 10–38% during summer and 30–38% during the winter. NYISO, 2007.

[8] There are limited wind measurements in some airport locations, but these have large data gaps. This data must be purchased from the Institute for Hydrology, Meteorology and Environmental Studies (IDEAM).

[9] Note that a more simple approach to account for wind speed variations with height is as follows: $V_z = V_h(z/h)^a$ where V_z and V_h are wind speeds at heights z and h, and where $h > z$, with $a = 0.16$ [12].

[10] Data obtained from the programe "Calculador de potencia" that is available online at: (DANISH WIND INDUSTRY ASSOCIATION http://www.windpower.org/es/tour/wres/pow/index.htm).

Table 2
The α, β, wind mean velocity (m/s) and standard deviation (m/s) monthly values at 60 m height that were used for the simulation of wind velocity and power generated.

	January	February	March	April	May	June
$\bar{V}$	9.36	9.87	9.92	9.62	9.47	10.38
σ	1.46	1.35	1.36	0.72	1.19	0.70
α	7.55	8.69	8.68	16.68	9.53	18.79
β	9.97	10.44	10.49	9.93	9.97	10.68

	July	August	September	October	November	December
$\bar{V}$	10.68	9.92	7.76	6.98	7.37	8.37
σ	0.88	1.39	1.57	1.51	1.18	1.13
α	15.04	8.48	5.67	5.27	7.35	8.82
β	11.06	10.51	8.39	7.58	7.86	8.85

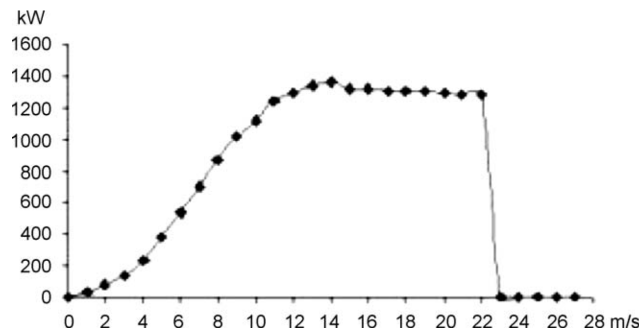

Fig. 1. Wind generator power curve used in simulation.

The regression equation for this curve, in the generation range is:

$$P = 0.0668V^4 - 3.9209V^3 + 73.832V^2 - 411.5V + 699.87 \text{ with an } R^2 = 0.9984 \quad (19)$$

The simulated wind farm has a nominal installed capacity of 50 MW and 39 wind generators. Table 3 presents data on the mean monthly generation (MW h) and its standard deviation, obtained from Monte-Carlo simulation of wind regime for Puerto Bolivar, Colombia.

Table 3 shows that the months with the highest energy generation are June and July, with mean velocities of 10.68 m/s and 10.38 m/s, respectively. On the other hand, the months with the lowest generation are October and November, with mean velocities of 6.98 m/s and 7.37 m/s, respectively.

From the simulated data, the wind farm's capacity factor is calculated. For a facility with an installed capacity of 50 MW, the maximum energy that could be generated under a 100% capacity factor in one year is 438,000 MW h. In average, however, the energy generated during a year in the simulated wind farm under monthly wind velocity variations in the selected site is 197,220 MW h. From this, the capacity factor of this wind farm is 0.45.

Table 3
Data on the mean monthly generation (MW h) and its standard deviation, obtained from Monte-Carlo simulation of wind regime for Puerto Bolivar, Colombia.

Month	Mean monthly generation [MW h]	Standard deviation [MW h]
January	17,380.7	6121.6
February	19,518.6	5708.6
March	19,723.6	5735.8
April	18,436.9	3118
May	17,789.1	5084.9
June	21,707.8	2935.9
July	22,939.6	3662.7
August	19,728.7	6138.4
September	10,842.9	5975
October	7866.0	5196.5
November	9035.0	4375.7
December	13,048.3	4665.9

Table 4
Calculated wind capacity under the simulated wind regime using the month of January as the critical period.

Methodology	PJM	NYISO	Spain
Capacity [MW]	16.3	24.2	25.6
Capacity [%]	32.6	47.73	5126
Firm energy (MW h year)	142,788	211,992	224,256

6. Capacity assessment with selected methodologies

The methodologies selected to calculate firm capacity for wind power (PJM, NYISO, and Spain Market) were evaluated in a critical hydrology period typical for Colombia. In addition, the methodologies were evaluated for the periods stipulated in their respective markets. That is, the respective firm capacity was assessed with each methodology under the Colombian wind regime.

According to what is established in Colombian regulation, resolution CREG 071 for hydropower plants, ENFICC will be calculated as the minimum energy that a hydropower plant can provide under critical hydrological conditions [2].

With these considerations, using the monthly generation model, the critical hydrology month in Colombia is selected according to Colombian rainfall data.

The months in the dry season with the most critical conditions (least rainfall) are selected for the Andean region (where most of hydropower plants are located in Colombia): January and February. These months have a precipitation that average 50–100 mm below the monthly average in Colombia [9].

Based on the previous discussion, the month of January was selected as a month of critical hydrology (as stipulated by Colombian regulation) for the calculation of firm energy.

Thus, the selected methodologies were assessed for the month of January, obtaining the following results of calculated firm capacity (represented as installed capacity, percentage of installed capacity, and annual firm energy (MW h) that the power plant would guarantee, again for the January wind regime). These results are presented in Table 4.

With these results, it is clear that at least with respect to firm capacity the most favourable methodology for power project investors is the one used in the Spaniard Market. However, it is also viable to implement the NYISO methodology (due to the slight difference between this and the Spaniard methodology). On the other hand, PJM's methodology provides a low Capacity Value, which is not going to provide remarkable income for possible investors.

7. Financial evaluation

According to resolution CREG 071 of 2006 and to the results of the first firm energy obligations auction performed in Colombia (May 2008), the potential 50 MW[11] wind power project's financial evaluation was carried out.

The financial model considered the following elements:

[11] The potential wind power project was studied with the conditions of Puerto Bolivar, in a region with possibly similar wind resource conditions as the current wind farm in the northern of Colombia.

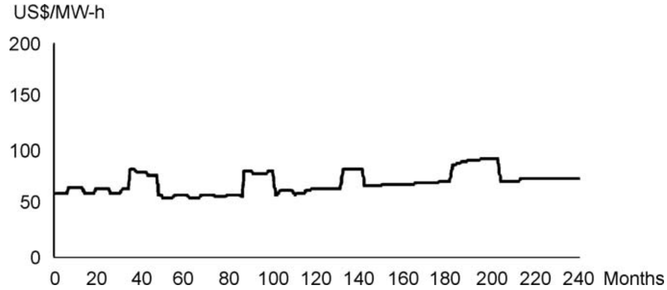

Fig. 2. Monthly evolution of market energy prices for the base case price scenario. Monthly price of energy [US$/MW h] vs. month.

Analysis horizon: A 20-year operation horizon was considered, which corresponds to the maximum validity period for the assignation of firm energy obligations [2].

Clean Development Mechanism: The following value was used to calculate the potential remuneration for the sale of tons of CO_2 equivalent emission reductions:

$$795\ \mathrm{TonCO_2/GW\text{-}h} \tag{20}$$

In addition, a sale price sensitivity analysis varying between $10\,y\,25\ \ (\mathrm{US\$/TonCO_2})$ was carried out.

Tributary legislation: Decree 2755 of 2003 exempts wind power projects from paying income tax during the first 15 years.

Capacity/firm energy remuneration: The calculated capacity was remunerated according to the price for the reliability payment that was obtained from the first firm energy auction performed; that is, at US$ 13,998/MW h.[12]

Depreciation and equipment costs: The equipment cost used for the analysis was of US$ 2000/installed kW, according to estimates of equipment costs conducted by the Lawrence Berkeley National Lab in 2008.

A lineal depreciation model was used for the financial analysis as follows:

Civil works depreciation: 20 years.
Equipment depreciation: 10 years and
Differed investment depreciation: 5 years.

Electricity sale income: Income for the sale of power was simulated according to wind regimes, taking into account the monthly distribution and the power curve of the selected wind turbine. As it was explained earlier, it was not possible to obtain the inter-daily and interannual wind regime variation and it was assumed that the wind regime is not affected by the El Niño weather phenomenon. The produced electricity will be remunerated according to an energy price model (USD$/MW h) that takes into account the hydropower behaviour and the energy demand scenarios generated by UPME[13] [15].

Three price scenarios were simulated and analyzed, as explained below:

Base scenario: The scenario considers four periods of critical hydrology of different intensities. The demand is simulated according medium energy scenario established by UPME. Fig. 2 presents the monthly price behaviour of the base case scenario.

Critical scenario 1: This scenario also considers four periods of critical hydrology but it uses the critical demand scenario established by UPME. Fig. 3 presents the monthly price behaviour of the critical case scenario 1.

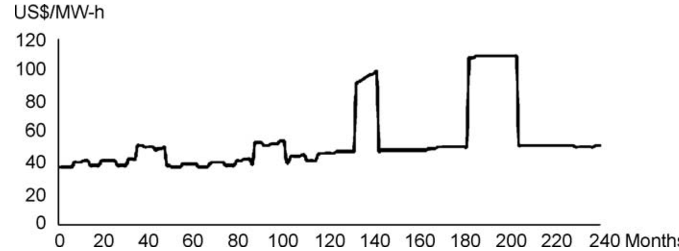

Fig. 3. Monthly evolution of market energy prices for the critical case price scenario 1. Monthly price of energy [US$/MW h] vs. month.

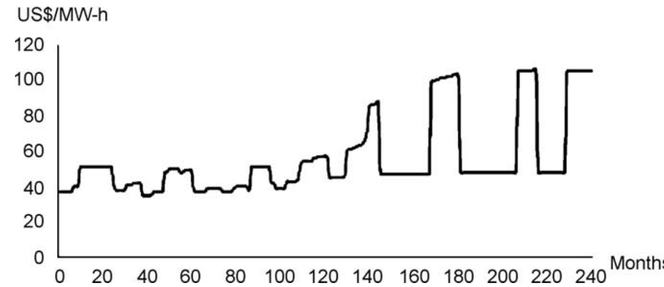

Fig. 4. Monthly evolution of market energy prices for the critical case price scenario. Monthly price of energy [US$/MW h] vs. month.

Critical scenario 2: This scenario uses a more critical hydrology period, simulating eight periods of critical hydrology and using the high demand scenario established by UPME. This scenario is presented in Fig. 4.

7.1. Results

The wind power project was analyzed for the three previously mentioned scenarios. The analysis was based on the Net Present Value, before and after-taxes, for each of the price case scenarios and the sale price interval of the sensibility to the value of the ton of CO_2 displaced. To obtain the results, one hundred runs of the financial and generation model were carried out. These were based in Monte-Carlo simulations of the wind regime and for each of the price scenarios mentioned above. The analysis was carried out based on the average of the one hundred runs that correspond to each of the price scenarios and values of the sensibility to the sale price of the ton of CO_2 displaced. The following section presents the results of the financial analysis for each one of the price scenarios.

7.1.1. Base case scenario results

The following graphics show the mean Net Present Value (NPV) behaviour (before and after-tax) obtained through Monte-Carlo modelling and considering a base scenario market energy price vs. the CO_2 value per displaced ton under the Clean Development Mechanism (CDM).

The mean NPV (either before or after-taxes) has a linear behaviour with respect to the CO_2 values per displaced ton. As it is observed in Figs. 5 and 6, under this base case scenario and for the CO_2 price range analyzed, the project is not viable under none of the three firm capacity remuneration methodologies.

To understand the CO_2 prices necessary for wind power projects to be viable under the base scenario, a linear regression and extrapolation of these functions were run to find the break-even price for displaced CO_2 (when NPV = 0). Table 5 shows the results for both before and after-tax analysis.

[12] The price index was updated according to that reported by the US Department of Labor Statistics of US$ 1.0176.

[13] This model was developed for a project conducted in 2000: *Opciones de Manejo del Recurso Hídrico en el Sector Eléctrico en Colombia*, elaborated for the National University of Colombia, COLCIENCIAS and ISA.

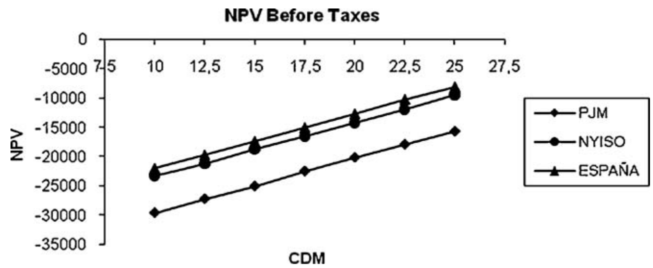

Fig. 5. NPV before-taxes under base case price scenario with Monte-Carlo sensibility modelling. CDM in US$/ton CO_2e and NPV in thousand US$.

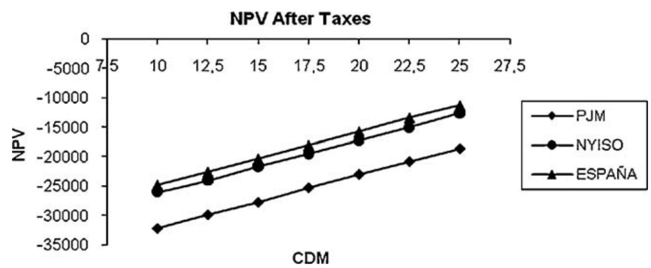

Fig. 6. NPV after-taxes under base case price scenario with Monte-Carlo sensibility modelling. CDM in US$/ton CO_2e and NPV in thousand US$.

Table 5
Break-even CO_2 prices for wind power projects to be viable. Base case price scenario, before and after-taxes.

Methodology	Price per ton CO_2 displaced *before*-taxes	Price per ton CO_2 displaced *after*-taxes
Spain	33.58	37.42
NYISO	35.44	39.32
PJM	41.75	45.54

According to these results CO_2 prices need to be quite high for wind projects to be viable under the base scenario. In addition, the results indicate that the most favourable firm capacity remuneration methodology is the one used in the Spanish Market, being closely followed by the NYISO methodology, while the methodology that provides the least feasibility is PJM's.

7.1.2. Critical case scenario 1 results

Figs. 7 and 8 show the mean NPV behaviour (before and after-taxes) obtained through Monte-Carlo modelling and considering the critical scenario 1 market energy price vs. the value per displaced ton of CO_2under the Clean Development Mechanism (CDM).

As expected (from the previous analysis) mean NPV has a linear relationship with displaced CO_2 price.

Under this scenario, it is observed that in the before-tax analysis, wind power projects start to be viable around US$ 20/CO_2 ton when the Spanish and the NYISO methodologies are applied. In the after-tax case, although the NPV values are higher than the previous base case scenario, projects are still not viable for the CO_2 price sensibility range. For wind power projects with the PJM methodology, NPV values are below zero for both the before and after-tax cases, in the CO_2 price sensibility range.

As with the base case scenario, linear regression and extrapolation of the functions were performed to find the break-even price for displaced CO_2 (when NPV = 0). Table 6 shows the results.

As with the previous case, the table shows the CO_2 prices at which wind projects become viable. Under this critical scenario 1, CO_2 break-even prices are lower than in the base case scenario. Again, the methodology that makes the projects more viable is the Spanish methodology, while PJM's is the methodology that makes them least viable.

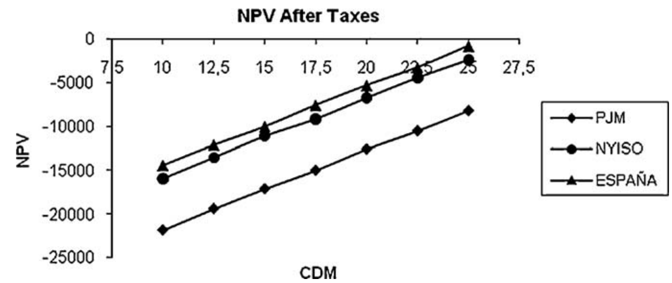

Fig. 8. NPV after-taxes under critical case price scenario 1 with Monte-Carlo sensibility modelling. CDM in US$/ton CO_2e and NPV in thousand US$.

Table 6
Break-even CO_2 prices for wind power projects to be viable. Critical case price scenario 2, before and after-taxes.

Methodology	Price per ton CO_2 displaced *before*-taxes	Price per ton CO_2 displaced *after*-taxes
Spain	20.79	25.93
NYISO	22.35	27.49
PJM	28.94	34.03

7.1.3. Critical case scenario 2 results

Figs. 9 and 10 show the mean NPV behaviour (before and after-taxes) obtained through Monte-Carlo modelling when considering the critical scenario 2 market energy price vs. the value per displaced ton of CO_2 under the Clean Development Mechanism (CDM).

As seen from Figs. 9 and 10, the before and after-tax NPV results for wind power projects become viable with the Spanish Market and the NYISO methodologies with the CO_2 prices analyzed. On the other hand, wind power projects under the PJM methodology continue not to be viable within the CO_2 sensibility price range (although the NPVs are less negative than in the two previous price scenarios).

Making a linear regression and extrapolating these functions, the break-even price for CO_2 displaced (when NPV = 0) was

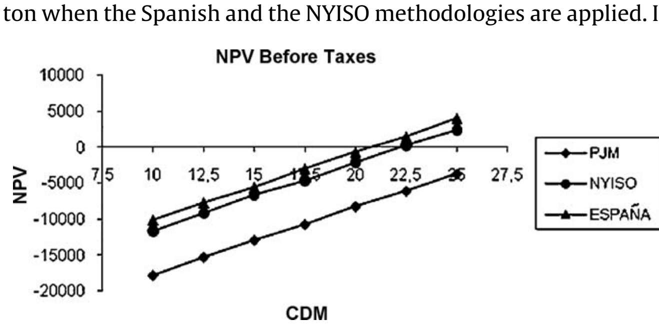

Fig. 7. NPV before-taxes under critical case price scenario 1 with Monte-Carlo sensibility modelling. CDM in US$/ton CO_2e and NPV in thousand US$.

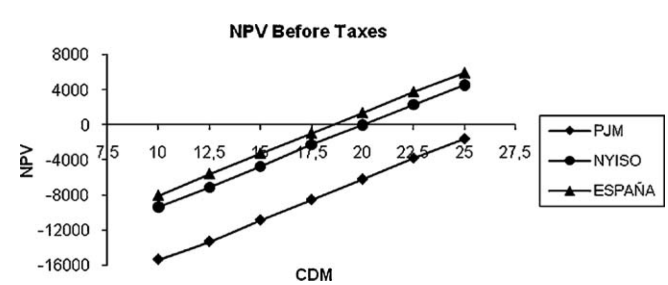

Fig. 9. NPV before-taxes under critical case price scenario 2 with Monte-Carlo sensibility modelling. CDM in US$/ton CO_2e and NPV in thousand US$.

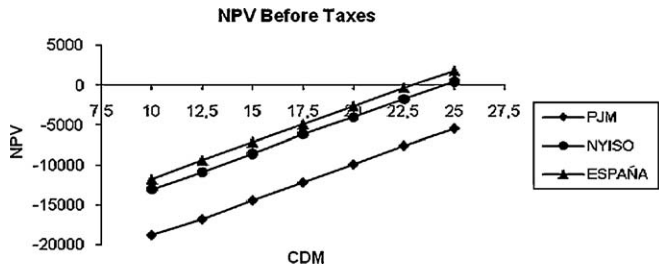

Fig. 10. NPV after-taxes under critical case price scenario 2 with Monte-Carlo sensibility modelling. CDM in US$/ton CO_2e and NPV in thousand US$.

Table 7
Break-even CO_2 prices for wind power projects to be viable. Critical case price scenario 2, before and after-taxes.

Methodology	Price per ton CO_2 displaced *before*-taxes	Price per ton CO_2 displaced *after*-taxes
Spain	18.75	22.99
NYISO	20.05	24.99
PJM	26.67	31.05

Table 8
Before-tax NPV standard deviation for the three methodologies under the critical price scenario 2 (thousand US dollars).

CDM value (US$/ton CO_2)	10	17.5	25
σ_{PJM}	1533.5	1077.6	1027.6
σ_{NYISO}	811.2	919.4	894.4
σ_{Spain}	873.3	1037	1085

Table 9
After-tax NPV standard deviation for the three methodologies under the critical price scenario 2 (thousand US dollars).

CDM value (US$/ton CO_2)	10	17.5	25
σ_{PJM}	1483	1033	985.7
σ_{NYISO}	776.1	881.6	858.1
$\sigma_{ESPAÑA}$	837.8	994.3	1041

calculated. Table 7 shows results for the before and after-tax analysis.

From the previous results it becomes clear that the firm remuneration methodology that is most appropriate to make wind power projects viable is the one used in the Spanish power market.

All of the results presented above were obtained from the mean of NPV distributions calculated in Monte-Carlo simulation. The results are related to a variation associated with the standard deviation distribution. Tables 8 and 9 show the standard deviation values obtained for the most favourable scenario (critical scenario 2) and for each of the firm capacity remuneration methodologies under analysis. These values are shown for specific CO_2 prices within the sensibility range.

As it can be seen, the standard deviation for the scenarios is large, compared to the NPV mean values of Fig. 2, the NPV assessed have a margin error (all standard deviation results are within a range of US$ 600,000 and US$ 1,600,000). This shows the volatility or risk that an investor faces when making a decision to invest in such projects if the remuneration is uncertain.

8. Conclusions

The existing methodologies for firm capacity calculation in Colombia have a retrospective-character; that is, they work with past data and power generation records, without considering the behaviour of the entire power system. The methodologies considered in this paper are easy to implement and consider factors for periods in which there is no historical data. This is particularly important for a country such as Colombia, where there is almost no historical wind power data.[14] The most appropriate methodologies for the case of Colombia, from the implementation point of view, are those that can be applied where wind generation is not mature, or there is lack of historical power generation data. This is the case for the methodologies selected in this analysis: Spain Power Market, NYISO and PJM. According to the assessment of power capacity under the simulated wind regime with these methodologies, the methodology that provides a higher Capacity Value, which is of interest for investors, is the Spanish Power Markets, followed with very close values by NYISO's, PJM's methodology provides very low Capacity Values and therefore from the investor point of view it is not appropriate, since evidently it would provide a lower remuneration.

According to the financial assessment analysis, which considers energy price scenarios, a sensitivity to price per ton of CO_2, and the remuneration for firm capacity (at the current remuneration price of the reliability payment), it is concluded that it is crucial that this type of incentives exist to make viable wind power projects in Colombia. With the absence of these incentives the Project's NPV would be negative before and after-taxes.

Consequently, after running the firm power remuneration methodologies under Colombian price scenarios and wind regime simulation with data from Puerto Colombia, the highest return for investors is obtained with scenario 2, when applying the Spain Power Market methodology. The authors suggest that a methodology similar to this be highly considered for implementation in Colombia.

In addition, it is suggested that these types of projects be carried out in the appropriate moment to take advantage of supply/demand gaps and critical hydrology, since energy power prices are highly influenced by these two variables.

Another variable to consider is the importance of participation in the Clean Development Mechanism. According to the sensibility analysis performed, none of the scenarios of the analyzed methodologies is viable unless there is simultaneously income from CO_2 reductions. This is very important because it demonstrates the "additionality" requirement under the CDM. According to the scenarios, the desirable US$ prices per ton CO_2 should be above the value of US$/20 ton CO_2.

Tax exemptions are another relevant issue. According to the analysis, although decree 2755 from 2003 establishes an income tax exemption for the first 15 years of operation (even if it were granted to all renewable energy projects), this incentive is not enough to guarantee project feasibility. Tax exemption is only a step and more actions are necessary in order to encourage investment in these types of projects.

As it can be seen, these types of projects need the combination of several factors to become viable. If the government is really interested in developing these technologies, it should concentrate in facilitating the factors under its control (e.g. firm capacity remuneration methodology, tax exemptions, etc.).

Lastly, Monte-Carlo simulation is presented as a low cost tool that can be used for prospection and planning in wind power projects. With relatively low data of wind potential from specific zones, a simulation model can be structured to generate a wide range of results, which can be used in several power generation software, and which then allow for the assessment of projects under different scenarios.

[14] As explained earlier, the power generation records and wind data of the only wind farm operating in Colombia are jealously kept and generally not available to possible wind power investors.

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